Study on the Machining Distortion of Thin-walled Part Caused by Redistribution of Residual Stress

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Abstract: In order to reduce the weight of airplane and increase its mechanical behaviors, more and more large integrated parts are applied in modern aviation industry. When machining thin-walled aeroplane parts, more than 90% of the materials would be removed, resulting in severe distortion of the parts due to the weakened rigidity and the release of residual stress. This might also lead to stress concentration and damage of the parts. The effect of material removal from residually stressed billet is simulated using FEA software MSC. Marc and the causations of distortion is analyzed. To verify the finite element simulation, a high speed milling test on aluminum alloy 7050T7351 is carried out. The results show that the simulation result is consistent with the experimental one. It is concluded that the release of residual stress is the main cause of machining distortion.

Key words: finite element method; simulation; residual stress; machining distortion

残余应力重分布引起的薄壁零件加工变形研究. 王兆峻, 陈五一, 张以都, 陈志同, 刘强. 中国航空学报(英文版), 2005, 17(2): 175-179.

摘　要: 现代航空工业中为减轻飞机重量, 提高飞机的各项机械性能, 整体构件越来越多地被使用。加工大型整体薄壁构件时, 有90%以上的材料被切削加工去除, 由于材料去除后零件刚度的降低以及应力的释放, 造成过大的加工变形。本文用MSC.Marc有限元软件仿真了铝合金预拉伸板材料去除对于加工变形的影响, 并分析了加工变形的成因。为验证有限元结果的正确性, 在高速数控铣床上加工了同样的试件。结果表明仿真结果与实验结果一致, 残余应力的释放与重分布是薄壁零件加工变形的主要原因。

关键词: 有限元法; 仿真; 残余应力; 加工变形

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Modern aviation is developing towards high speed and heavy load. A lot of thin-walled aeroplane components, machined from solid aluminum billets rather than assembled from separate parts, have been increasingly applied in modern aviation industry to reduce the assembly time/costs and to improve the performance of the planes. These parts are thin in thickness, complex in structure and tight in machining tolerance. Due to the weakened rigidity and the release of residual stress after more than 90% of the materials are removed, severe distortion is often observed on the parts, Fig. 1.

Presently, the procedure to machine a large-scale integrated part in workshops is often arranged as follows:

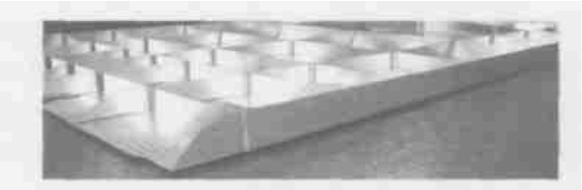

Fig. 1 The deformed shape of thin-walled part after machining

(1) Fix an aluminum blank on the worktable.

(2) Perform a 2-D machining on the top surface with small DOC and reach the size of the 2-D profile directly, *i.e.*, leaving no allowance for finishing.

(3) Machine the blank layer by layer till arriving at the final shape.

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(4) Unfasten the part from the worktable.

At this stage, unacceptably large distortions often occurres. The highly distorted part may no longer be able to serve its designated functionality or may require significant reworking to render its function. These problems result in high scrap rates and increase manufacturing costs.

It is assumed that the release and the redistribution of the residual stresses in the billet are the major reasons of the distortions. The residual stress comes mainly from the rolling process of the billets and is also influenced, though less significantly, by cutting force, fastening force, cutting temperature, *etc*. Many methods to eliminate residual stress have been adopted. After a rolled aluminum blank is stretched along rolling direction to produce 2.5% permanent distortion, its residual stress magnitude may drop 90%. Another effective method is uphill quenching[1]. Nevertheless, it seems impossible to eliminate the residual stress completely. Machining distortion may occur as long as the residual stress exists.

The residual stress and its measurement were extensively investigated during 1970 s to 1990 s[2-4]. The distribution of the residual stresses particularly in aluminum billets was studied by Wang, *et al*[5]. However, its effects on machining distortion and the technique to reduce the distortion have not yet been fully explored. The paper presented here detailes a research concerning the effect of material removal on the distortion of the thin-walled parts *via* FEM simulation and experimental work.

1 FEM Simulation of Machining Distortion

During the CNC machining process, many factors, such as residual stress, cutting force, cutting temperature, fastening force, fixture configuration *etc*. are not taken into consideration, when coding the CNC machining program. To reveal the real effects of these factors on the machining process, a finite element simulation can be adopted. The FEM simulation of the cutting process has great value to understand the cutting process and to reduce the number of experiments.

1.1 Material properties

The material of the part is aero-aluminum alloy 7050T7351. The alloy is assumed to be an elastic-plastic material. Its physical specifications are listed in Table 1.

Table 1　Physical parameters of aluminum alloy 7075T7351[6]

Properties	Value	Remark
Young's modulus	71 GPa	
Poission's ratio	0.33	
Density	2800 kg/m^3	
Thermal conductivity	155 W/m·℃	25℃
Specific heat	960 J/kg·℃	100℃

1.2 Geometry of the part

The blank of the part is a pre-stretched aluminum plate. Its dimension is 300 mm × 104 mm × 24 mm. A thin-walled structure is designed similar to a typical aero-plane component, see Fig. 2.

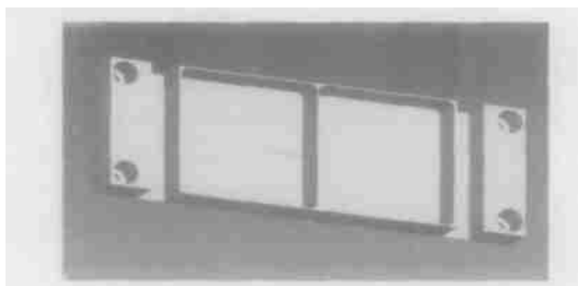

Fig. 2　Designed specimen

Due to its symmetry, the 1/2 model is used, and the model is divided into 49896 elements and 55600 nodes. Fig. 3 is the FEA model of the block in simulation.

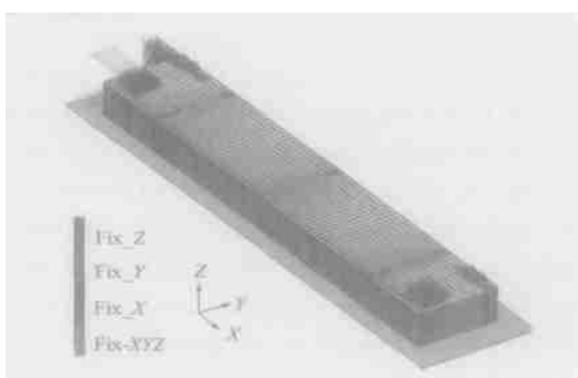

Fig. 3　FEA Model

1.3 Boundary conditions

The finite element method is a powerful tool to assess potential distortions caused by the machining process. It provides a good approximate solution to continuum problems. The FEA software MSC. Marc is used to analyze the distortions for it can define the elements to be inactive. This technique can simulate the metal removal action in cutting procedure.

Once the part is fixed on the worktable, it can not move to the table but can move away from it. Most FEA software, including MSC. Marc, does not provide single side constraint. In this paper contact analysis has been used for the solution of single-side constraint in order to simulate the real fixture more authentically. The worktable is considered as a rigid body in the FEA model, so the part can not move towards it.

1.4 Simulation Results

In the simulation, the part material is removed layer by layer. Each layer is 3mm in thickness except the last layer that is 2mm thick. The removed layer is set to be inactive to simulate the milling process. In order to study the deformation of the bottom point "A" is chosen, Fig. 4. Fig. 5 shows the deformation of point "A" after each layer is removed. Fig. 6 is the deformation nephogram when the removed layer is 9 mm in thickness.

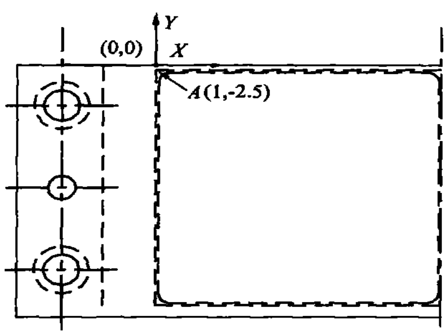

Fig. 4 Point selected to measure the deformation

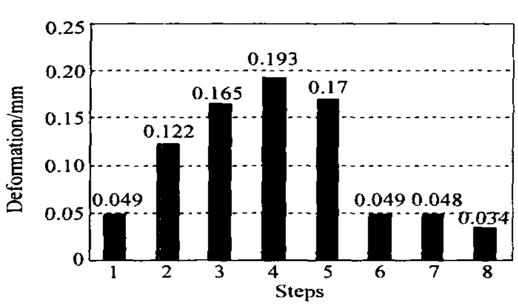

Fig. 5 Bottom deformation of the specimen

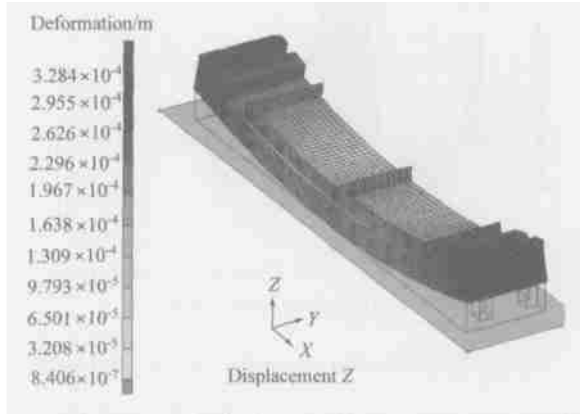

Fig. 6 Distortion when 9 mm layer is removed

It can be seen from Fig. 5 that the deformation increases step by step until the fourth layer is reached. Then it drops down from the fourth to the sixth layer. During the removal of the last three layers the deformation varies very little. It is anticipated that with more and more metal being removed, the distortion will increase.

The reason why the distortion decreases when half of the material has been cut away may be explained as follows.

With the removal of the residually stressed material, the remaining stresses in the workpiece redistribute to reach new equilibrium. For pre-stretched aluminum billets, the surface is more likely to exhibit tensile stress[7]. The inner part of the piece is therefore stressed compressively. That is, the stress changes from the top surface to the bottom in a tensile-compressive-tensile manner. The FEA results using MSC. Marc show that when three layers of totally 9 mm material have been removed, the stress distribution alters dramatically, see Fig. 7.

Although the overall stresses are still balanced, the concentration of the tensile stress in the upper part of the specimen will cause both ends of the specimen to deflect upwards, Fig. 6. As the machining progresses, the tensile stress within the lower part increases gradually. After the fifth layer has been cut away, the lower part tensile stress of the specimen becomes strong enough to balance the

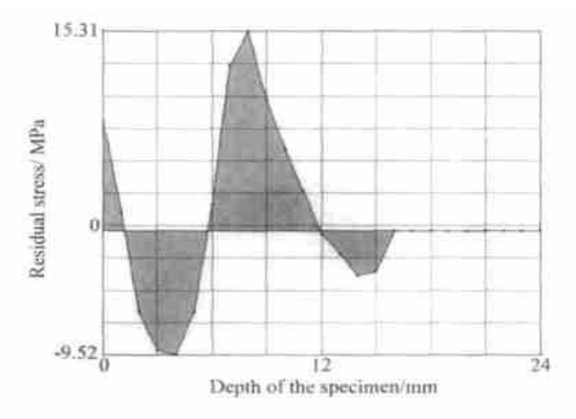

Fig. 7 Residual stress after removing the third layer

upper part one, as shown in Fig. 8, and the upward deflection reduces as a result. When the machining on the sixth to the seventh layer have been performed, most residual stresses, no matter tensile or compressive, are released and the distortion of the specimen decreases to a very low level, Fig. 5.

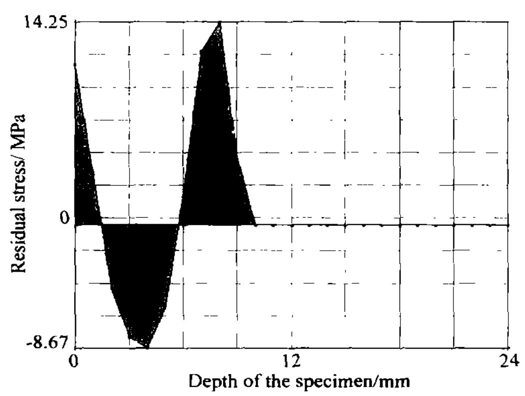

Fig. 8 Residual stress after removing the fifth layer

2 Experiment Verification

In order to verify the simulation results, the designed specimen part is machined on a Fidia CNC machining center, see Fig. 9.

Fig. 9 Machined specimen

The cutting speed is 18 000 r/min, the depth of cut is 0.5 mm, and the feed rate is 4000 mm/min. The distortion of the bottom of the part is measured in a coordinate measuring machine.

Table 2 shows both the simulated and measured values of distortion. It can be seen from Table 2 that the measured data increase in the former four steps, then decrease from the fifth step. The deformation does not change drastically in the last three steps. The measurement and the FEA simulation of distortion receive very similar changeable trend. Since the simulation result is derived under the assumption of neglecting cutting heat and tool vibration, there is relative error especially in the last step.

Table 2 The distortion of the bottom

Removed thickness/ mm	3	6	9	12
Simulated results/ mm	0.049	0.122	0.165	0.193
Measured data/ mm	0.068	0.139	0.192	0.218
Removed thickness/ mm	15	18	21	23
Simulated results/ mm	0.170	0.049	0.048	0.034
Measured data/ mm	0.180	0.088	0.081	0.069

3 Conclusions

With the removal of the first few layers on the specimen, distortion increases owing to uneven concentration of the stress.

The residual stress in the blank varies severely accompanied by the remove of material. This results in the machining deformation of thin-walled part. The release of the residual stress in the blank is the main cause of machining distortion especially for the thin-walled part.

After half of the material is cut away, the stress distribution becomes better balanced and the distortion reduces gradually. There is a critical value of material removal amount. When the amount of the material removed exceeds the critical value the machining deformation drives to steady.

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